Final Technical Report
NASA Grant NAG5–9493

Development of Submillimeter SIS Mixers and Broadband HEMT Amplifiers

Grant expiration date: April 30, 2004

J. Zmuidzinas, Principal Investigator

California Institute of Technology, 320-47, Pasadena, CA 91125, USA.

October 5, 2004

Contents

1 Introduction

This is the final technical report for NASA grant NAG5–9493, entitled "Development of Submillimeter SIS Mixers and Broadband HEMT Amplifiers". The goal of this project was to develop and demonstrate a new generation of superconducting tunnel junction (SIS) receivers with extremely wide instantaneous (intermediate–frequency, or IF) bandwidths, of order 12 GHz, along with the wideband low–noise microwave HEMT (high electron mobility transistor) amplifiers which follow the SIS mixer. These wideband SIS/HEMT receivers would allow rapid submillimeter wavelength spectral line surveys to be carried out, for instance with the NASA airborne observatory SOFIA, and could potentially be useful for future submillimeter space missions such as SAFIR. In addition, there are potential NASA earth science applications, such as the monitoring of the distribution of chemical species in the stratosphere and troposphere using the limb-sounding technique.

The overall goals of this project have been achieved: a broadband 200-300 SIS receiver was designed and constructed, and was demonstrated in the field through a test run at the Caltech Submillimeter Observatory on Mauna Kea, HI. The technical details are described in the appendices, which are primarily conference publications, but Appendix A also includes an unpublished summary of the latest results. The work on the SIS mixer design are described in the conference publications[1, 2] (appendices B and C). The "Supermix" software package that was developed at Caltech and used for the SIS design is also described in two conference papers[3, 4], but has been substantially revised, debugged, and extended as part of the work completed for this grant. The Supermix package is made available to the community at no charge[5]. The electromagnetic design of a radial waveguide probe similar to the one used in this work is described in a journal publication[6]. Details of the novel fabrication procedure used for producing the SIS devices at JPL are also given in an upcoming journal article[7]. Finally, details on the wideband HEMT amplifier design and noise characterization techniques are described in two publications[8, 9].

2 Personnel

This project involved personnel at Caltech and at JPL. The personnel at Caltech include: the PI; a research staff member, Frank Rice (33% time); a physics Ph.D. student, Chip Sumner; a visiting graduate student (from U. Michigan, EE dept.), Robert Hu; and a staff engineer, D. Miller. Rice performed the majority of the work developing the SIS mixer. Sumner assisted with the mechanical design of the waveguide block, constructed the room–temperature wideband IF system, and participated in the astronomical tests. Hu worked on the development of the IF amplifier. Miller is an electrical engineer who assisted in various aspects of the project. At JPL, the project included: Dr. S. Weinreb, who oversees the development of the IF amplifier; and Drs. H. G. LeDuc and A. Kaul, who developed novel techniques for fabricating the SIS devices.

3   Relevant Publications

[1] M. Sumner, A. Blain, A. Harris, R. Hu, H. G. LeDuc, D. Miller, F. Rice, S. Weinreb, and J. Zmuidzinas, "A wide–bandwidth, low–noise SIS receiver design for millimeter and submillimeter wavelengths," in *Proceedings far–IR, sub–mm, and mm detector workshop* (J. Wolf, J. Farhoomand, and C. R. McCreight, eds.), vol. NASA/CP-2003-211408, pp. 195–198, Washington, DC: NASA, 2003.

[2] F. Rice, M. Sumner, J. Zmuidzinas, R. Hu, H. G. LeDuc, A. I. Harris, and D. Miller, "SIS mixer design for a broadband millimeter spectrometer suitable for rapid line surveys and redshift determinations," in *Millimeter and Submillimeter Detectors for Astronomy* (T. G. Phillips and J. Zmuidzinas, eds.), pp. 301–311, Proc. SPIE, vol. 4855, Feb. 2003.

[3] J. Ward, F. Rice, G. Chattopadhyay, and J. Zmuidzinas, "Supermix: a flexible software library for high-frequency circuit simulation, including SIS mixers and superconducting elements," in *Tenth International Symposium on Space Terahertz Technology: Symposium Proceedings*, (Charlottesville, VA), pp. 268–281, University of Virginia, Mar. 1999.

[4] F. Rice, J. Ward, J. Zmuidzinas, and G. Chattopadhyay, "Fast harmonic balance of SIS mixers with multiple junctions and superconducting circuits," in *Tenth International Symposium on Space Terahertz Technology: Symposium Proceedings*, (Charlottesville, VA), pp. 282–297, University of Virginia, Mar. 1999.

[5] Supermix software; send email to `supermix@submm.caltech.edu`.

[6] J. Kooi, G. Chattopadhyay, S. Withington, F. Rice, J. Zmuidzinas, C. Walker, and G. Yassin, "A full–height waveguide to thin-film microstrip transition with exceptional RF bandwidth and coupling efficiency," *Int. J. IR and MM Waves*, vol. 24, no. 3, pp. 261–284, 2003.

[7] A. B. Kaul, B. Bumble, K. A. Lee, H. G. LeDuc, F. Rice, and J. Zmuidzinas, "Fabrication of wide–IF 200–300 GHz SIS mixers with suspended metal beam leads formed on SOI," *J. Vac. Sci. B*, 2004. in press.

[8] R. Hu and S. Weinreb, "A novel wide-band noise-parameter measurement method and its cryogenic application," *IEEE Trans. Microwave Theory Tech.*, vol. 52, pp. 1498–1507, May 2004.

[9] R. Hu, "An 8–20 GHz wideband LNA design and the analysis of its input matching mechanism," *IEEE Micr. Wireless Comp. Lett.*, 2004. in press.

A Final Status Summary (2004)

Broadband heterodyne SIS spectrometer prototype: first results

F. Rice[a], H. LeDuc[c], A. Harris[d], S. Hu[b], M. Sumner[a], J. Zmuidzinas[a]

[a]California Inst. of Technology; [b]U. of Michigan; [c]Jet Propulsion Laboratory; [d]U. of Maryland

1. INTRODUCTION

The broadband heterodyne SIS receiver system described elsewhere (reference 1) has been assembled and tested both in the laboratory and during two observing runs on the Cassegrain focus of the 10 meter telescope at the Caltech Submillimeter Observatory on Mauna Kea, Hawaii. Here we present a brief summary of the initial results.

2. FABRICATION AND ASSEMBLY

The SIS mixer chips were fabricated at the JPL Microwave Experiment Systems and Technology Section (reference 2). Figures 1 – 4 are photographs of the chips.

The mixer block containing the RF waveguide, mixer chip, and SIS DC bias board was assembled and combined with a corrugated feed horn, lenses, and superconducting magnet to suppress unwanted Josephson tunneling currents in the SIS junction. A high frequency connector on the mixer block assembly allowed the broadband IF low noise amplifier (LNA) to be closely coupled to the mixer. Illustrations of the complete RF and LNA assembly are included (figures 5 and 6).

The receiver assembly is mounted to the cold plate in a LHe dewar with the feed horn facing downward along the cylindrical dewar axis. A mylar window and a flourogold IR block transmit the RF into the dewar and to the feed horn. A thin mylar beam combiner adds the local oscillator (LO) signal to the RF from the telescope. Once it leaves the dewar the 4 – 18 GHz IF is further amplified and split up into several 4 GHz wide bands which are each down converted to 4 – 8 GHz. These outputs are then presented to WASP II analog autocorrelating spectrometers for analysis. The complete receiver system is shown mounted on the CSO telescope in figures 7 and 8.
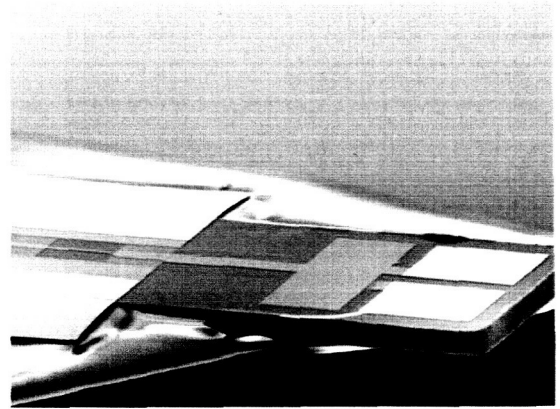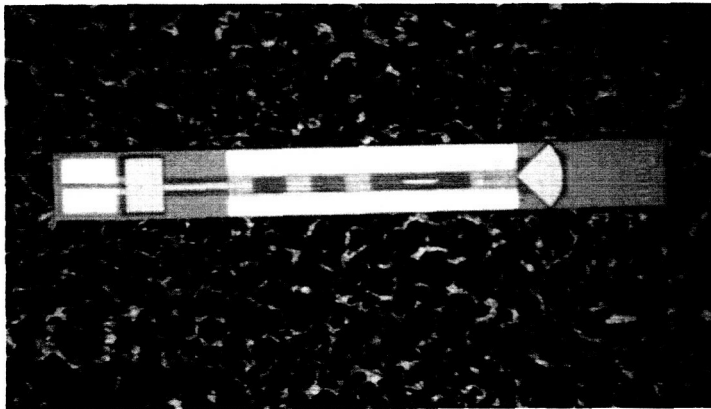

Figure 1 (left): A SIS mixer chip from the first production batch. The silicon substrate dimensions are 1.99 mm × 0.23 mm, 25 microns thick. The "1.5 um" markings denote the SIS junction dimensions on this particular chip; several junction sizes are included on each wafer. The waveguide probe (antenna) is the pie-shaped structure on the right; the rectangular wire bond pads for the IF and DC bias connections are on the left.

Figure 2 (right): Close-up scanning electron micrograph of the wire bond area of a chip from a later production batch which included gold beam leads for ground connections along the long edges of the chip.
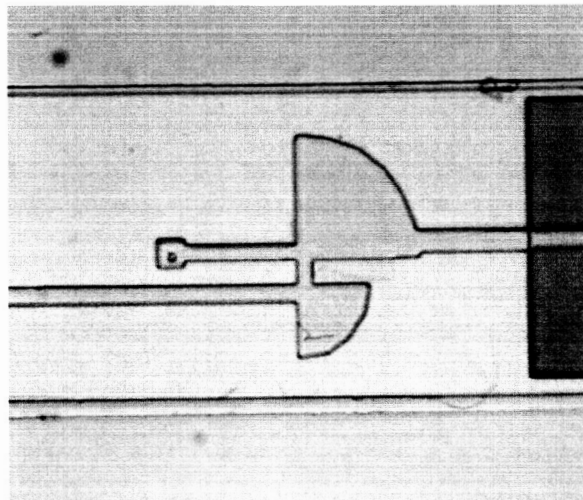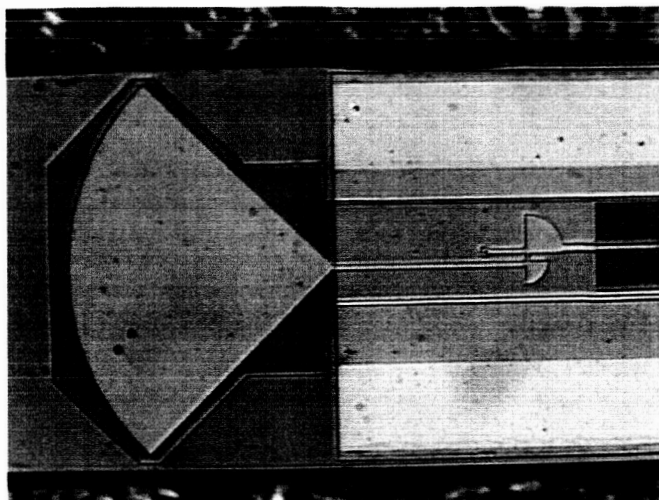
Figure 3 (left): The waveguide probe and RF section of the SIS mixer chip. The waveguide probe has a radius of 150 microns and an opening angle of 90 degrees. The mixer chip is mounted in a channel perpendicular to the RF waveguide axis. The apex of the probe is aligned with the waveguide wall. The probe and wiring are 0.4 micron thick niobium. The brown structure in the photo is the silicon oxide dielectric layer (0.35 micron thick) separating the wiring from a niobium ground plane deposited on the silicon surface. The gold layers provide a wire bonding surface for the ground plane.

Figure 4 (right): Close-up of the RF section and SIS junction on the mixer chip. The SIS junction is the tiny square within the square area to the left of the larger pie-shaped region of the wiring layer (light blue in this photo). The RF signal enters from the left; the IF signal exits to the right.
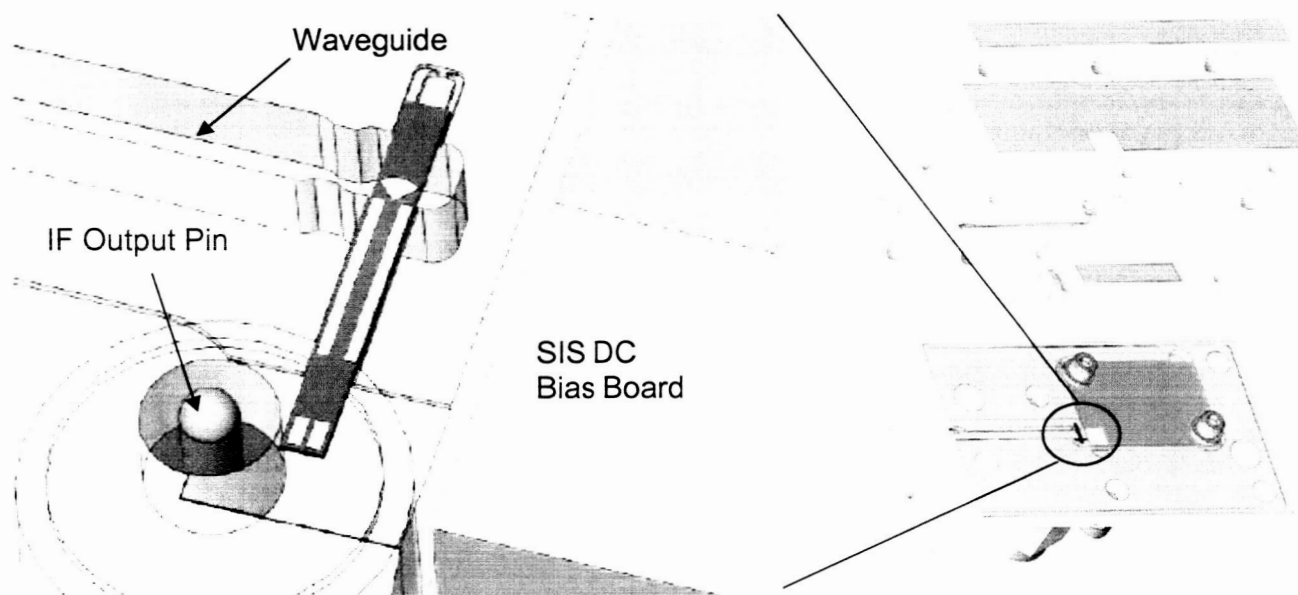

Figure 5: Mixer block assembly. The two halves are machined from brass and then gold plated. The SIS mixer chip is mounted and wire bonded to the IF connector and the SIS bias board, then the two halves of the block are mated.
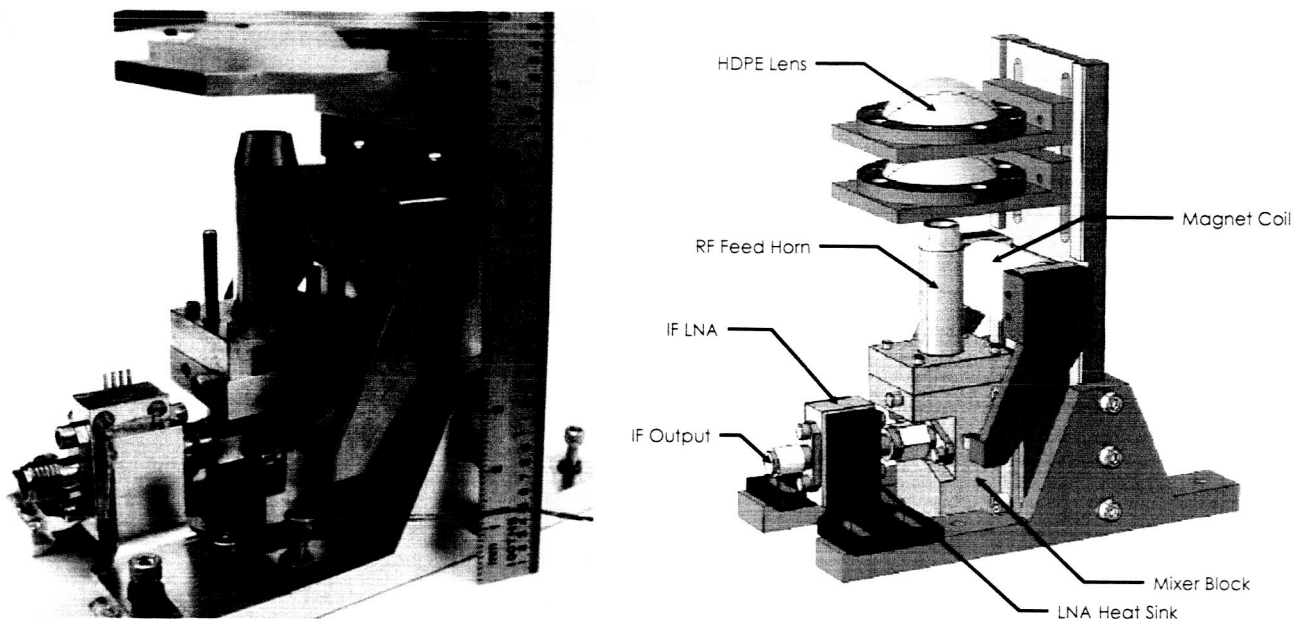
Figure 6: Receiver assembly. The CAD model on the right identifies significant subassemblies found in the photo on the left. This assembly is mounted on the LHe cold plate in the receiver dewar.
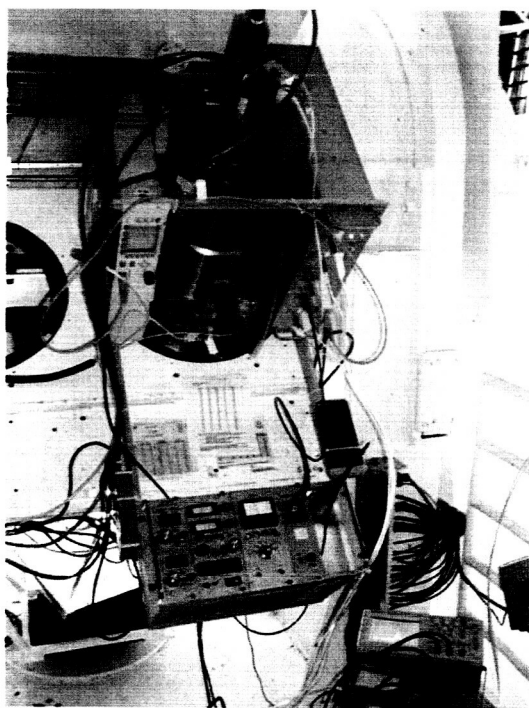

Figure 7 (left): The receiver system mounted on the CSO 10 meter telescope in March 2004. The gold-anodized dewar containing the SIS mixer and LNA is mounted on the telescope Cassegrain focus relay optics. The IF down converter subsystem is mounted just to the right of the dewar; it splits the broadband IF output into four separate bands and down converts each subband to 4-8 GHz. The equipment mounted below the dewar consists of the several power supplies needed to operate the receiver.
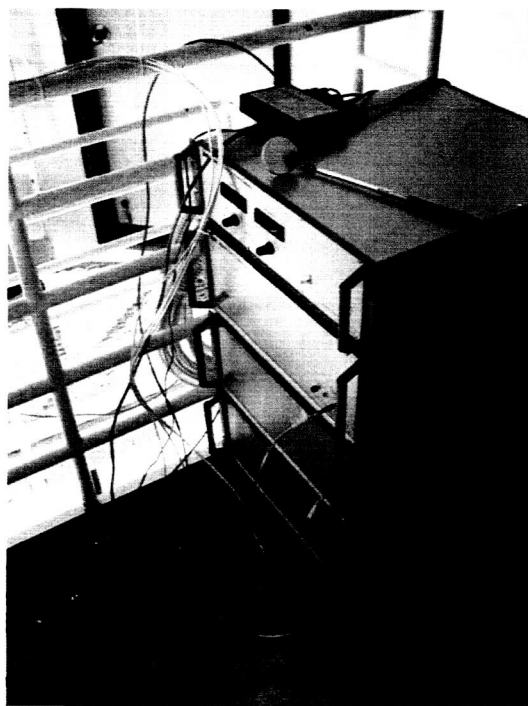
Figure 8 (right): The WASP II analog autocorrelation spectrometers. The four 4-18 GHz signals from the receiver are fed to this array of four WASP II units. Each has a bandwidth of 4.25 – 7.75 GHz with 128 channels of spectral resolution. The top unit in the stack of boxes is the power supply for the WASPs.
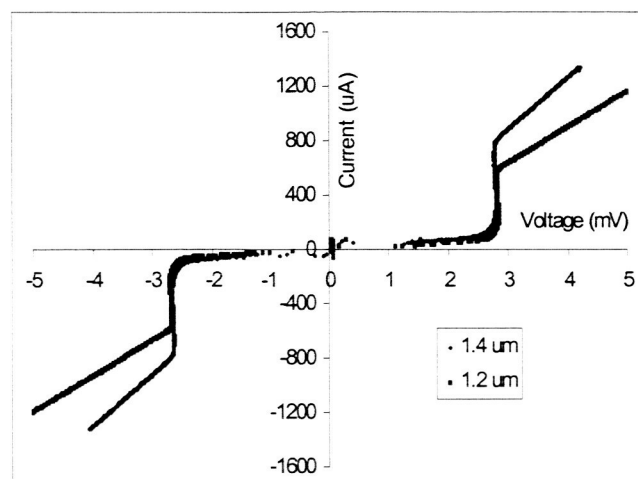
3. INITIAL RESULTS

Figure 9: Measured SIS DC IV characteristic curve for 1.2×1.2 micron and 1.4×1.4 micron SIS devices produced at JPL. These are very high critical current density (J_c = 44 KAmp/cm^2) devices; SIS Normal Resistance (R_n) values are 4.3 and 3.0 Ohms, respectively.
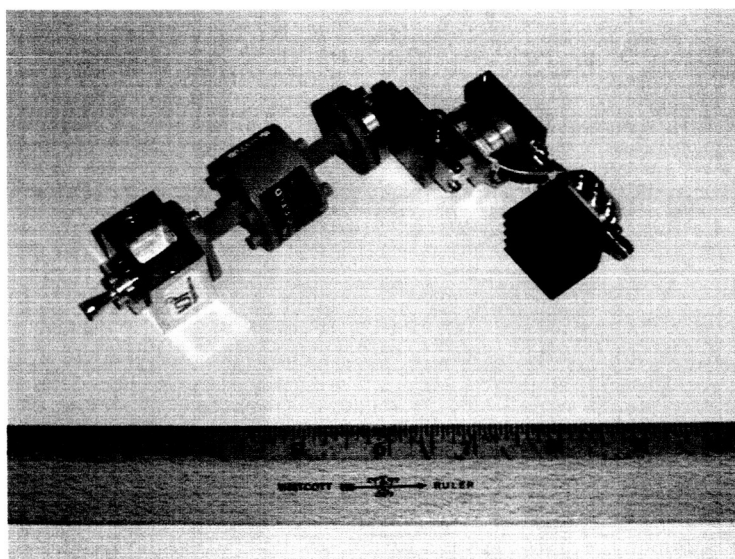

Figure 10: Active amplifier-multiplier chain for the receiver local oscillator (LO). The signal from a microwave generator (13.3 – 18.7 GHz) is input to the connector on the right in the photo. The LO output (200 – 280 GHz) is radiated from the conical horn on the left. The chain has a multiplication factor of 15 and can provide approximately 100 microwatts of output power across the LO band. The chain was custom designed and fabricated by Virginia Diodes, Inc.

The mixer chip was designed for SIS devices with a critical current density (J_c) of 16 KAmp/cm^2, which would result in a normal resistance (R_n) of approximately 8.5 Ohms for a 1.3×1.3 micron SIS junction. The first batch of devices fabricated exhibited a much higher J_c (approx 30 KAmp/cm^2) and, consequently, a rather lower R_n. The second batch had near design J_c junctions. The latest batch, the first production run with beam leads (figure 2), again exhibited very high J_c (44 KAmp/cm^2).

Typical DC current-voltage (IV) curves for the latest batch are also shown (figure 9). The quality of the IV curves for these devices is quite good, so the SIS mixer chip is currently being redesigned to accommodate the higher current density of these devices.
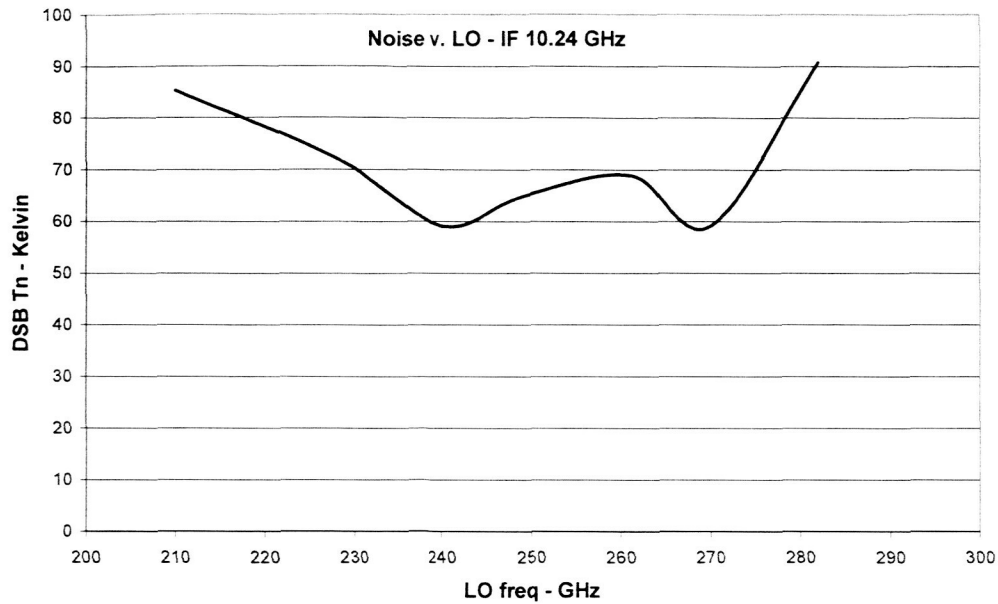

Figure 11: Laboratory measurement of receiver noise temperature v. LO frequency. The measurements were obtained by using the hot-cold load technique and measuring the total receiver output noise power in a 250 MHz bandwidth centered at 10.24 GHz. The IF LNA used was a 4 – 14 GHz design with a measured noise temperature of approximately 4.5 K across the IF band.

Figure 12: Laboratory measurement of receiver noise temperature v. IF frequency. The measurements were obtained by using the hot-cold load technique and measuring the receiver output noise spectrum using a microwave spectrum analyzer. As in figure 11, the IF LNA used was a 4 – 14 GHz design with a measured noise temperature of approximately 4.5 K across the IF band. The dropout in the response at 8.5 GHz has been determined to be due to a resonance caused by the SIS DC bias board.
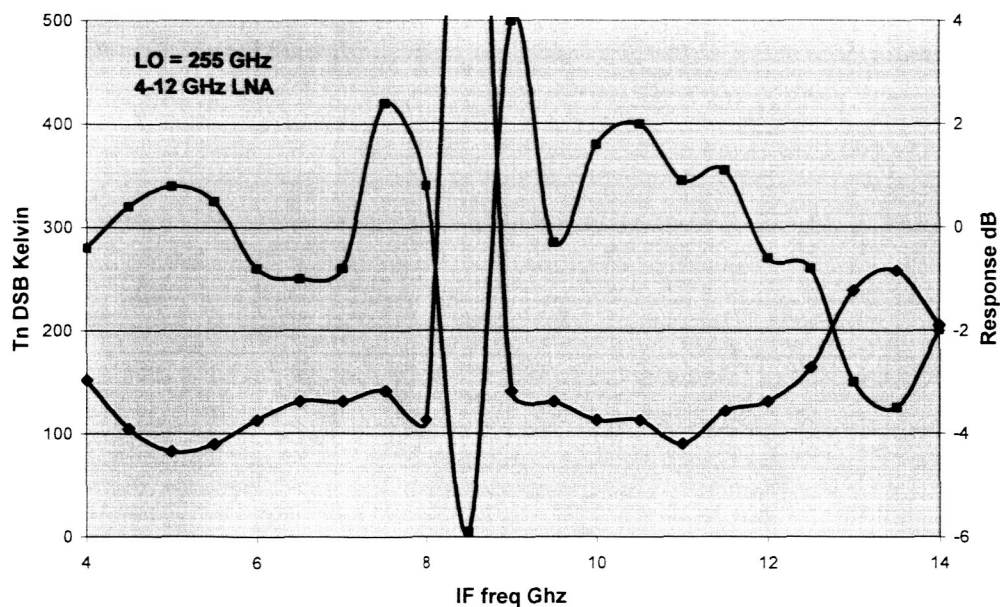
Following very brief lab verification tests, the receiver was installed at the CSO for an initial engineering run in August 2003. The Local Oscillator (LO) used for this observing run consisted of an active amplifier-multiplier chain driven by a microwave signal generator. The active amplifier-multiplier chain is pictured in figure 10. First light of the receiver was on August 28. The performance during this first run was quite disappointing, but subsequent laboratory efforts resulted in significant improvements in performance. Lab measurements of receiver noise performance are presented in figures 11 and 12. Following these lab efforts a second observing run was completed in March 2004. A typical result from that run is presented in figure 13.
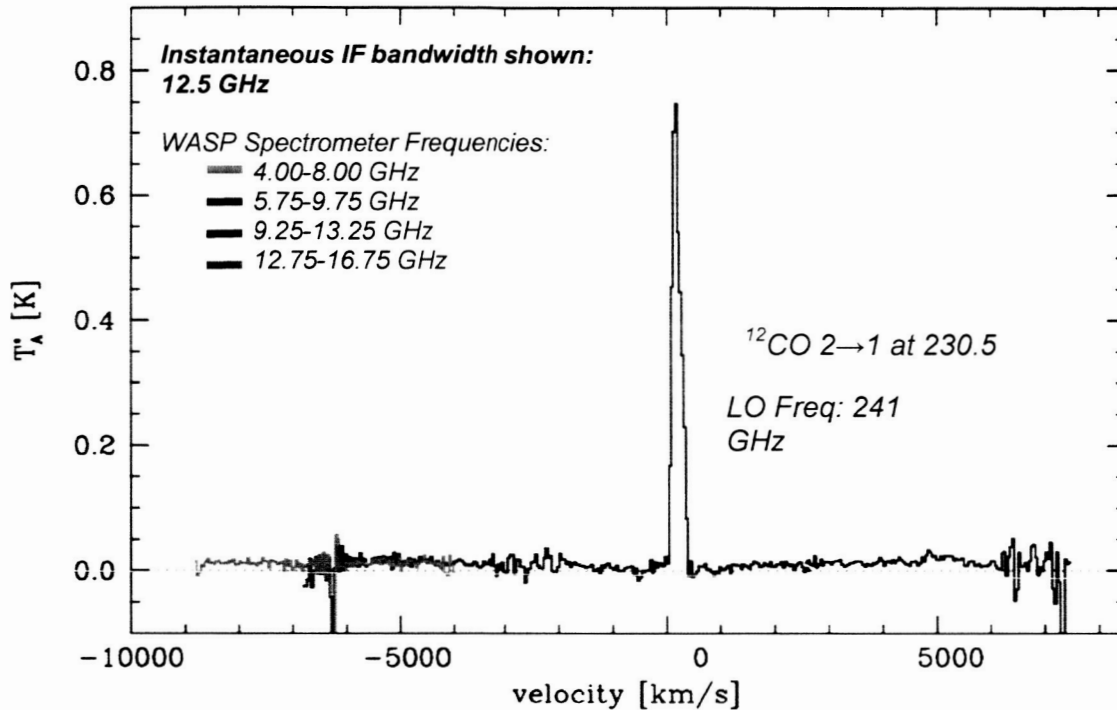

Figure 13: CSO observation of a star-forming region of the galaxy M82 on March 22, 2004. The amount of precipitable water vapor above the Mauna Kea summit was quite high, resulting in a zenith optical depth of 0.21 at 230 GHz. The receiver+telescope+atmosphere system temperature was approximately 500 K. The total observing time was 33 minutes. The receiver configuration included four WASP II spectrometers and is shown in figures 7 and 8.

REFERENCES

1.   F. Rice, M. Sumner, J. Zmuidzinas, R. Hu, H. LeDuc, A. Harris, D. Miller, "SIS mixer design for a broadband millimeter spectrometer suitable for rapid line surveys and redshift determinations," *Proc. SPIE* Vol. 4855, p. 301-311, Feb 2003.

2.   Anupama B. Kaul, Bruce Bumble, Karen A. Lee, and Henry G. LeDuc, "Fabrication of wide-IF 200-300 GHz SIS mixers with suspended metal beam leads formed on SOI," *Jour. Vacuum Science and Technology-B*, accepted, publication TBD.

B   2002 SPIE Conference Paper

SIS mixer design for a broadband millimeter spectrometer suitable for rapid line surveys and redshift determinations

F. Rice[a], M. Sumner[a], J. Zmuidzinas[a], R. Hu[b], H. LeDuc[c], A. Harris[d], D. Miller[a]

[a]California Inst. of Technology; [b]U. of Michigan; [c]Jet Propulsion Laboratory; [d]U. of Maryland

ABSTRACT

We present some detail of the waveguide probe and SIS mixer chip designs for a low-noise 180–300 GHz double-sideband receiver with an instantaneous RF bandwidth of 24 GHz. The receiver's single SIS junction is excited by a broadband, fixed-tuned waveguide probe on a silicon substrate. The IF output is coupled to a 6–18 GHz MMIC low-noise preamplifier. Following further amplification, the output is processed by an array of 4 GHz, 128-channel analog autocorrelation spectrometers (WASP II). The single-sideband receiver noise temperature goal of 70 Kelvin will provide a prototype instrument capable of rapid line surveys and of relatively efficient carbon monoxide (CO) emission line searches of distant, dusty galaxies. The latter application's goal is to determine redshifts by measuring the frequencies of CO line emissions from the star-forming regions dominating the submillimeter brightness of these galaxies. Construction of the receiver has begun; lab testing should begin in the fall. Demonstration of the receiver on the Caltech Submillimeter Observatory (CSO) telescope should begin in spring 2003.

Keywords: SIS, submillimeter, mixer, spectrometer, broadband, heterodyne

1. INTRODUCTION

One of the most exciting recent discoveries in astronomy has been the detection of dozens of high redshift, very luminous galaxies using bolometer cameras on submillimeter-band telescopes. Dusty and obscured at short wavelengths, these galaxies have proven to be difficult to identify using optical and near infrared telescopes, rendering these instruments nearly useless for accurate redshift determinations[1]. The warm molecular gas in the star-forming regions of these galaxies exhibits prominent line emissions of the rotation spectrum of carbon monoxide (CO) at frequencies which are integral multiples of 115 GHz and which extend well into the submillimeter range. The 180–300 GHz atmospheric window provides an ideal frequency range for redshift determination using these emissions. Unfortunately, existing instruments have very narrow instantaneous bandwidths (no more than 4 GHz). Searching the entire 100 GHz window would be prohibitively time consuming with such instruments. The motivation for this project has been to demonstrate a system which can overcome this limitation.

Superconductor-insulator-superconductor (SIS) devices are in principle capable of extremely large instantaneous bandwidths and noise temperatures within a few degrees of the quantum limit. We are developing a sensitive, broadband heterodyne spectrometer for the Caltech Submillimeter Observatory (CSO) which will be suitable for CO line searches and redshift determinations. The prototype receiver features a double-sideband design using a single SIS mixer excited by a full bandwidth, fixed-tuned waveguide probe. The 6–18 GHz IF output provides an instantaneous RF bandwidth of 24 GHz (double-sideband). The IF signal will be analyzed by an array of analog autocorrelation spectrometers (WASP II[2]) providing a total of 384 channels. The wide instantaneous bandwidth and the single-sideband receiver noise temperature goal of 70 Kelvin will result in an instrument which should be capable of detecting CO line emissions with redshifts approaching $z = 2$. Additional applications of the instrument include rapid line surveys of galactic and extragalactic molecular clouds and on-the-fly mapping of tropospheric composition as part of a new NASA satellite mission concept under study at JPL to monitor atmospheric chemistry and pollution.

2. SIS DEVICE AND DESIGN CONSIDERATIONS

Heterodyne detection of the RF signal is accomplished using a SIS junction quasiparticle mixer. The SIS junction must have reasonably low leakage current and a sharp nonlinearity in its DC current-voltage characteristic in order to achieve high conversion gain and low noise. Because of its significant capacitance, an SIS junction's impedance rolls off at high

frequencies. In a mixer design, the roll-off frequency of the SIS junction impedance must be approximately equal to or greater than the design RF bandwidth. Finally, the mixer must be able to accommodate the total RF noise power received without saturation.

Through analyses and trade studies, it was determined that a single-junction mixer design would be able to achieve the performance goals while using reasonably inexpensive and reliable SIS manufacturing technology available at JPL. The heart of the mixer is the single Nb-AlN-Nb SIS junction. The 1.3×1.3 micron junction's critical current density (J_c) of about 16 kA/cm^2 will provide a normal resistance (R_n) of 8.5 ohms and capacitance of 150 fFarad^3. This value of J_c was chosen so that the R_nC product corresponds to an impedance roll-off frequency of 125 GHz, high enough that the bandwidth limitation imposed by the Bode-Fano theorem should be minimal. The large area and moderate current density (for AlN barriers) will require only inexpensive UV contact lithography and mature JPL technology, so junction quality will be high, and subgap-to-normal resistance ratios in excess of 20 should be attainable.
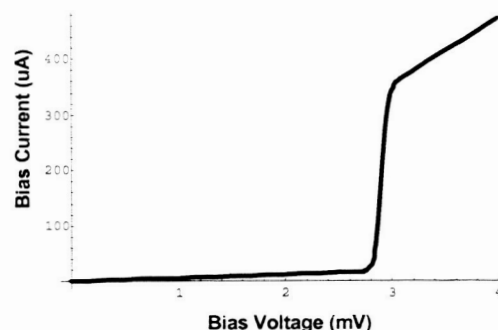

Figure 1: Modeled SIS DC IV characteristic curve for an 8.5 ohm R_n device. This characteristic curve was used throughout the mixer design process to model the SIS junction. The curve was used to generate the fully nonlinear response of the heterodyne detector model using the SuperMix software package, including predictions of mixer noise and conversion gain. The SIS IV curve depicted is typical of Nb-AlN-Nb, moderate J_c SIS junctions produced at JPL.

For the purposes of the receiver design, the assumed leakage current and nonlinearity of the SIS junction are slightly conservative and should be achievable with reasonable yields (Fig. 1). Although an R_n of only 8.5 ohms may seem low compared to typical waveguide probe impedances of 30-50 ohms, it is well within the capability of a suitably designed RF matching network. This low value for R_n simplifies the IF matching problem, increasing conversion gain, and mitigates saturation effects.
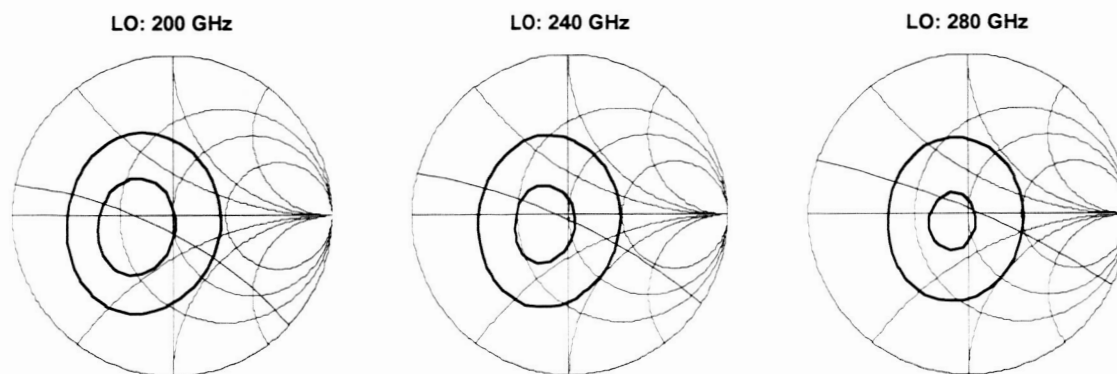

Figure 2: Effects of RF embedding impedance on mixer performance. The Smith charts show how mixer T_n and stability vary with RF embedding impedance for a number of LO frequencies. The oval contours are for SSB mixer T_n of 5K and 10K over the quantum limit; the gray regions denote the range of RF embedding impedance for which the mixer output impedance has a negative real part (IF instability). All charts are for upper sideband and an IF frequency of 10 GHz. The Smith charts are normalized to the SIS normal resistance, R_n.

Having chosen to use a single SIS device for the active mixing element, a study was conducted to determine the RF and IF embedding impedances seen by the SIS required for optimum noise performance and stability of the mixer. RF embedding impedance determines the noise temperature of the mixer as well as the IF stability. It must be carefully controlled or the SIS will present a negative real impedance to the IF circuit, resulting in receiver instability or even

oscillation. Typical results of the RF embedding analysis (Fig. 2) demonstrate that the optimum RF embedding impedance should be less than R_n and slightly capacitive; the impedance must be kept from going above R_n or becoming inductive to avoid IF instability. As illustrated in Fig. 2, the best achievable mixer T_n for an SIS with performance like Fig. 1 is about 3-5 Kelvin (single-sideband) over the quantum limit (note that Fig. 2 includes the SIS device capacitance as a part of the embedding impedance seen by the junction).

Once the RF embedding impedance is optimized for mixer T_n and IF stability, the mixer conversion gain is controlled by the IF embedding impedance. Typical results of the IF embedding analysis (Fig. 3) show that excellent conversion efficiency is achievable, but RF reflection gain (instability) obtains when conversion gain is high. Excessive RF reflection gain can cause standing waves in the telescope optics, resulting in large gain variations for small changes in RF frequency. This problem can be mitigated by careful optical design; in principle, well-designed dewar and telescope optics should provide sufficient return loss so that a few dB of RF reflection gain from the SIS can be tolerated.
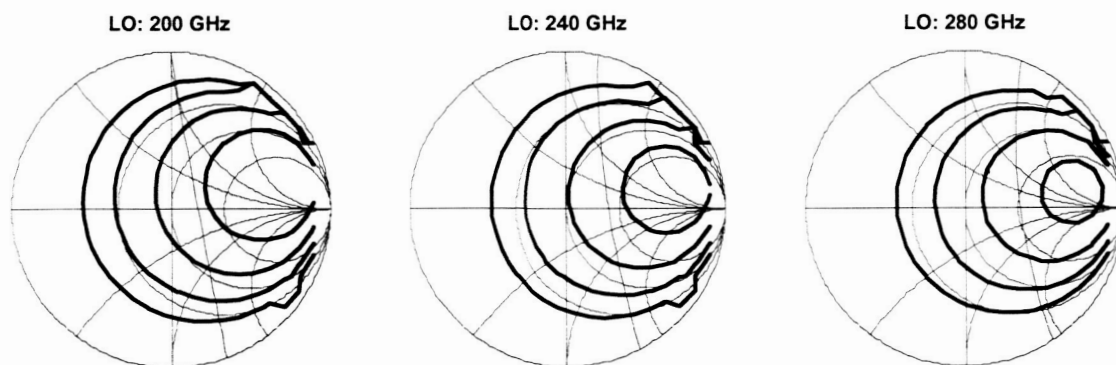
LO: 200 GHz	LO: 240 GHz	LO: 280 GHz

Figure 3: Effects of IF embedding impedance on mixer performance. The Smith charts show how mixer conversion gain (S_{21}) and RF stability vary with IF embedding impedance for a number of LO frequencies. The bold contours are for S_{21} = -2, 0, +2, and +4 dB (the smaller contours represent higher gains); the gray regions denote the range of IF embedding impedance for which the mixer input impedance has a negative real part (RF instability). All charts are for upper sideband and an IF frequency of 10 GHz. The assumed RF embedding impedance is that which minimizes mixer T_n for the specified LO and IF frequencies. The Smith charts are normalized to twice the SIS normal resistance ($2 \times R_n$).

3. WAVEGUIDE PROBE

Coupling from the receiver to the telescope is accomplished by a corrugated, cylindrical feed horn exciting a rectangular waveguide via a broadband cylindrical-rectangular transition section. A waveguide probe terminates the waveguide and couples RF radiation from it to the thin-film SIS detector circuit. The 37×16 mil (940×406 micron) waveguide has a cutoff frequency of 160 GHz. The 180–300 GHz RF band (1.7:1 frequency ratio) includes 75% of the single-mode frequency range of the waveguide. Providing efficient waveguide to thin-film microstrip coupling over the large RF bandwidth is nontrivial, since the waveguide impedance varies by a 1.9:1 ratio and the waveguide wavelength ($?_g$) varies by a 3.1:1 ratio over this bandwidth.

The performance of a waveguide probe can be characterized by its complex-valued reflection coefficient as seen by the RF circuitry ($?_{probe}$). To achieve an efficient, broadband receiver design, $?_{probe}$ should:

- be slowly-varying and predictable over the RF band;
- be reasonably tolerant of machining errors and material property variations;
- correspond to a nearly real-valued impedance which can be matched to the SIS detector using a simple RF design;
- avoid the use of moveable waveguide elements which must be adjusted to tune the receiver during operation.

Following a several-month study, design, and development effort a suspended-substrate waveguide probe design which satisfies all of the above requirements has been achieved. Derived from a design studied by Withington, et. al.[4], the probe consists of a 90-degree radial sector on a dielectric substrate oriented so that the radial sector lies in a plane defined by the E-field of the TE_{10} mode and its propagation direction along the waveguide. A channel extending from the wall of the waveguide supports the substrate so that the probe is fixed in its proper position (Figs. 4 and 5). The design is notable in several respects:

- the substrate material is 25 micron thick silicon, which results in a significantly lower probe impedance than does a quartz substrate for this probe configuration;
- the probe has a radial stub geometry rather than the traditional rectangular, resulting in significant bandwidth improvement over earlier designs[5];
- the substrate extends completely across the waveguide; RF energy is more efficiently coupled to the waveguide, reducing probe reactance;
- a small waveguide step upstream of the probe is used to further reduce probe impedance variation with frequency and to improve the tolerance of the probe performance to machining errors.
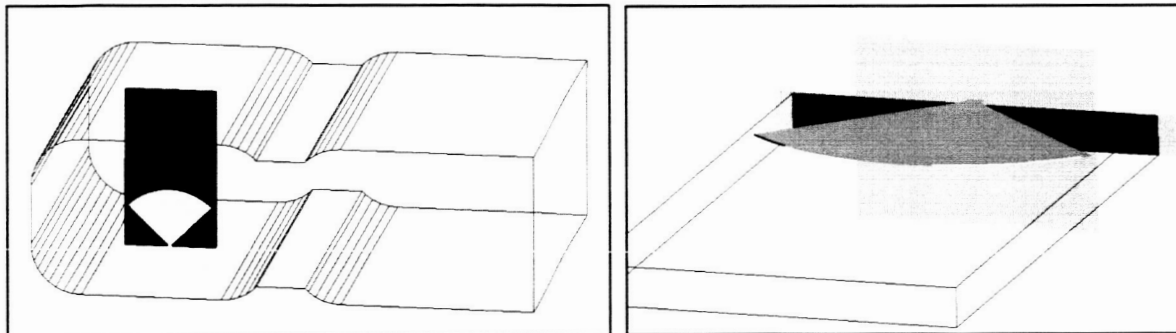

Figure 4 (left): General arrangement of the waveguide and probe. The 37×16 mil waveguide is terminated by a back short 11 mils behind the probe centerline. The silicon substrate (dark gray) is 230 microns wide and 25 microns thick (9.1×1.0 mil) and extends completely across the height of the waveguide. The 90-degree radial probe (light gray) has a 150 micron (5.9 mil) radius and consists of a 0.40 micron thick niobium film deposited on the surface of the substrate: it is terminated in a thin-film microstrip transmission line connected to the RF detector circuitry. The short reduced-height section of waveguide just upstream of the probe serves as a capacitive tuning element and significantly improves the probe performance over the wide bandwidth required. All waveguide features are designed to be machined with a 5 mil fillet radius as shown.

Figure 5 (right): Detail showing how the probe substrate is mounted in a channel extending from the waveguide wall. The silicon substrate (dark gray and gray outline) is shown protruding from the waveguide wall. The light gray area shows the channel within which the substrate is suspended. The channel includes air gaps extending 1.0 mil above and 2.0 mil below the substrate, which ensure that the cutoff frequency for wave propagation within the channel remains above the operating RF range of the receiver. The substrate and its channel extend approximately 1 mm (40 mil) beyond the waveguide wall.

Probe development required several hundred hours of detailed electromagnetic (EM) field simulations followed by optimization of the waveguide back short and tuning element. The EM field simulations used Ansoft HFSS®, a commercial program. The optimizations were accomplished using the SuperMix library, a Caltech-developed software package described later. Design of the substrate channel was guided by a theoretical analysis of EM wave propagation in partially-filled rectangular waveguide.

Final calculation of the predicted probe performance (Fig. 6) was accomplished using an HFSS analysis of the complete waveguide and probe assembly using the manufacturing drawings. These results have been validated by lab network analyzer measurements of a scale model probe of a very similar design. As can be seen in the figure, predicted probe impedance is very nearly constant and real over the entire 180–300 GHz RF frequency range, with an average value of 36+j3 ohms.
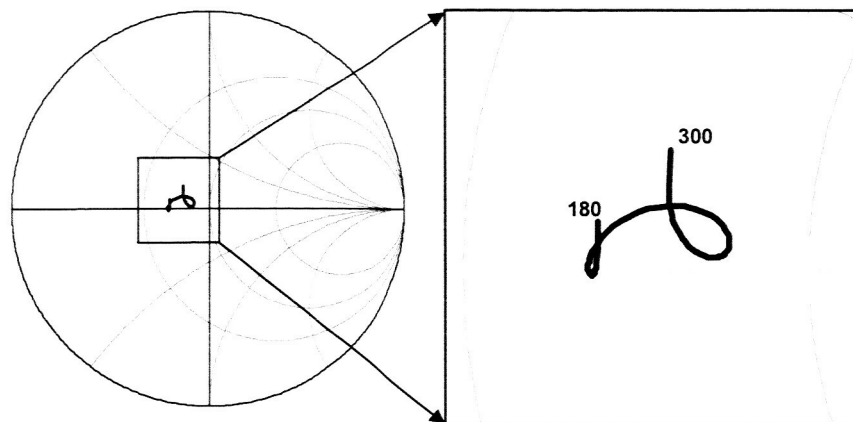
Figure 6: Waveguide probe performance. Predicted performance of the waveguide probe design shown in Fig. 4, as calculated using Ansoft HFSS and validated using a laboratory scale model of a similar design. The complex-valued reflection coefficient as seen by the RF circuitry, $?_{probe}$, is plotted on a Smith chart normalized to 50 ohms. The curve covers 180-300 GHz, the operating range of the receiver. $?_{probe}$ stays well within 0.1 of its average value (corresponding to an impedance of 36+j3 ohms) over that frequency range.

4. RF MATCHING NETWORK

The SIS junction is coupled to the waveguide probe using an RF matching circuit which must tune out the SIS device's large capacitance and transform the probe impedance so that the SIS sees the optimum RF embedding impedance. It must accomplish these tasks over the entire RF frequency range of the receiver, keeping the RF embedding impedance seen by the SIS under tight control in order to minimize mixer noise temperature while avoiding mixer instabilities and oscillation at the IF output. The RF circuit should be compact and simple in order to reduce its capacitive load on the IF output circuit and its loss at RF frequencies. Finally, the RF design must be tolerant of typical UV contact lithography alignment and etching errors with only minor performance degradation.

Straightforward analysis of the RF embedding impedance requirements demonstrates that a simple parallel or series inductance tuning element (to resonate out the SIS device's parallel capacitance) is inadequate to achieve the broadband, fixed-tuned performance required. Analyses and optimizations of various networks have demonstrated that a properly-designed C-L-C "pi" network can meet the bandwidth goal. Additional impedance transformer stages are needed to lower the 36 ohm probe impedance to the $R_n/2$ or so required at the input to the pi network.

The final RF matching network (Fig.'s 7 and 8) is implemented in thin-film, superconducting, microstrip circuitry using niobium ground plane and wiring layers separated by a SiO dielectric layer. The circuitry is deposited on the waveguide probe substrate along with the probe itself and the SIS junction. Although conceptually the RF circuit is a ¼-wave transmission line transformer followed by a lumped-element LC ladder (Fig. 7), the analysis and optimization were performed using a full model of the thin-film, superconducting, microstrip circuitry and SIS device implemented with the SuperMix software package. The effects of stray capacitance and inductance at the circuit junctions and corners were analyzed using the HFSS 3-D electromagnetic simulator and were included in the SuperMix model. The RF embedding impedance of the design (Fig. 9) is nearly optimum throughout the RF frequency range. The resulting mixer noise performance should remain within a few degrees of the quantum limit throughout the design RF and IF bandwidth (Fig. 10).
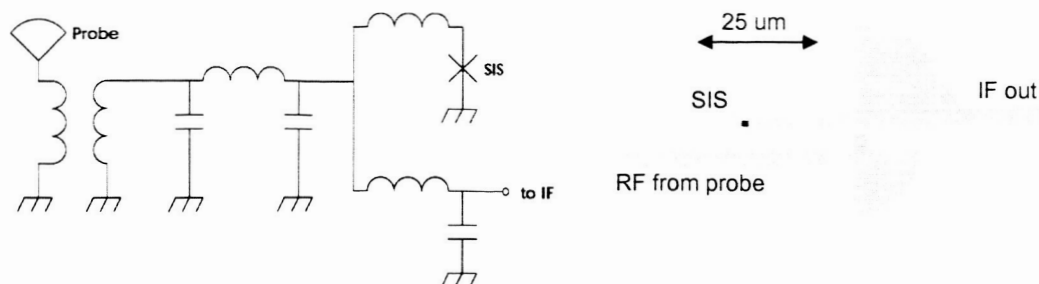
Figure 7 (left): Conceptual equivalent circuit of the RF matching network. The waveguide probe is connected to the SIS using a ¼-wave transformer followed by a lumped-element LC ladder. The capacitance associated with the SIS junction is not shown as a separate element in this figure.

Figure 8 (right): Thin-film microstrip layout of the RF matching network. The microstrip transmission line coming in from the left carries the LO and RF signals from the waveguide probe; only the final portion of its 108.6 micron length is shown. The radial stubs serve as parallel capacitors, the short sections of narrow microstrip as series inductors (Fig. 7). The IF output is extracted from the fan end of a radial stub, which is a particularly low impedance point in the RF circuit.
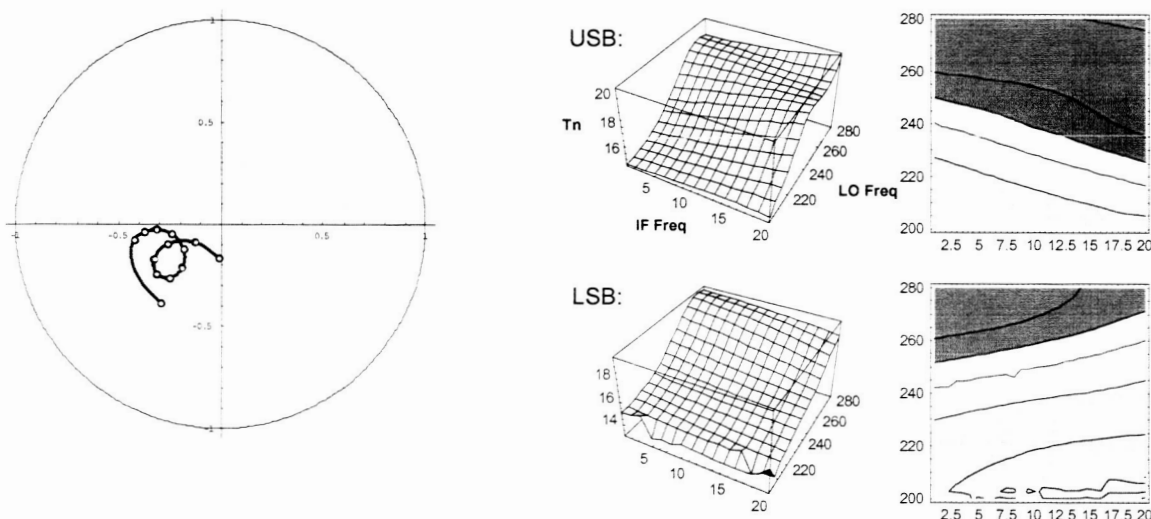

Figure 9 (left): Smith chart showing the design RF embedding impedance seen by the SIS, resulting from the circuit made up of the waveguide probe, RF matching network, and SIS capacitance. The frequency range is 180–300 GHz; the circles are spaced at 10 GHz intervals. The Smith chart is normalized to the SIS $R_n = 8.5$ ohms. Compare with the optimal embedding impedance charts in Fig. 2.

Figure 10 (right): Predicted mixer noise performance. Shown are 3-D and contour plots of mixer single-sideband T_n v. LO and IF frequencies for both upper sideband (USB) and lower sideband (LSB) detection. Contours are at 1 Kelvin intervals; $T_n < 16K$ (including quantum noise!) are in light gray, $T_n > 18K$ are in dark gray. Mixer noise is generally less than 6K over the quantum limit throughout the frequency range of the receiver.

5. RF CHOKE AND IF MATCHING NETWORK

The IF output signal from the SIS junction must be coupled efficiently to the load presented by the low noise IF preamplifier. At the same time, RF energy must be isolated from this low-frequency output, or receiver sensitivity will

suffer. A single thin-film circuit fabricated along with the RF matching network on the surface of the waveguide probe substrate is used to perform both the IF matching and RF isolation services.
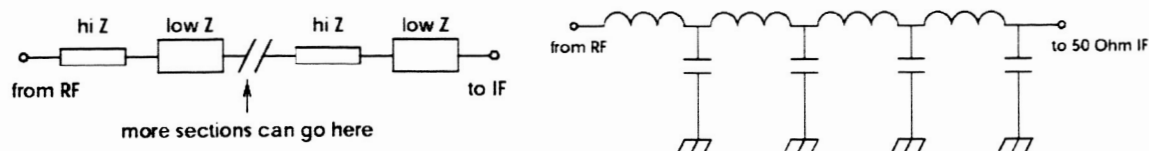

Figure 11: RF choke and IF matching network. By cascading high impedance–low impedance pairs of ¼-wave transmission lines at RF frequencies, effective isolation of the IF output from the RF circuit can be achieved (left). At the much lower IF frequencies, these transmission line sections behave as a lumped-element LC ladder network (right). The impedances of the transmission lines can be chosen to optimize the IF load matching. A total of four high-low pairs are used in the receiver circuit, with a ¼-wave design frequency of 287 GHz and a characteristic impedance of 90 ohms for the high impedance sections.

The IF output is extracted from the fan end of a radial stub in the RF circuit (Fig. 8). The fan end of the radial stub is convenient because the impedance of the RF matching network is quite low at that point of the circuit. Consequently effective RF isolation can be achieved by ensuring that the IF circuit presents a high impedance relative to this very low impedance part of the circuit. Generating a high RF impedance at the input to the IF circuit is achieved by cascading a series of high and low impedance ¼-wave transmission lines (Fig. 11). Each high/low pair transforms its load impedance by a factor equal to the square of the impedance ratio of the pair, so quite high impedances can be maintained at the input of this RF choke structure even though the IF load may present large impedance variations within the RF bandwidth.
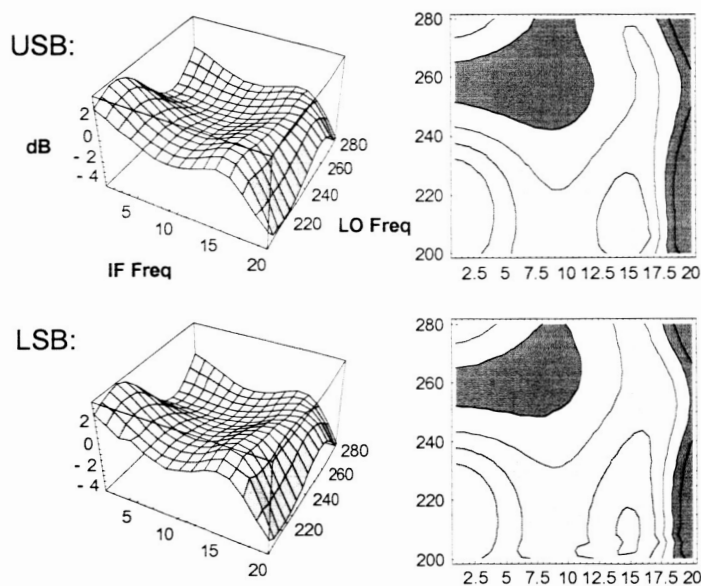

Figure 12: Predicted mixer conversion efficiency. Shown are 3-D and contour plots of mixer single-sideband conversion gain (dB) v. LO and IF frequencies for both upper sideband (USB) and lower sideband (LSB) detection. Contours are at 1 dB intervals; gains > 0 dB are in light gray, gains < −1 dB are in dark gray. The mixer provides conversion gain over most of the operating frequency range of the receiver.

At IF frequencies the cascade of ¼-wave lines behaves as a lumped-element LC ladder structure, since IF wavelengths are an order of magnitude longer than RF wavelengths. As a result, the RF choke structure can also be used to match the

IF load to the SIS device, tuning out the reactances of the SIS capacitance and the RF matching network in the IF band and maximizing mixer conversion gain. Design of the IF structure involves selecting the number of sections, choosing the ¼ wavelength RF design frequency, and selecting the characteristic impedance of each section in order to maximize the conversion gain of the mixer when driving a specified IF load while maintaining a sufficient RF stability margin and isolation of the IF circuit from the RF signal. Since high impedance lines are required, the design uses a combination of CPW and microstrip lines in the choke. Using SuperMix to perform the circuit optimization, the design has good predicted conversion efficiency over the entire receiver operating range, minimizing the impact of IF amplifier noise performance on the overall sensitivity of the receiver (Fig. 12).

6. CHIP LAYOUT AND MIXER BLOCK

The SIS and RF circuitry are deposited directly onto the silicon dielectric substrate supporting the waveguide probe using UV contact lithography. The thin-film superconducting circuitry is deposited on the silicon substrate in three layers: a 0.2 micron niobium ground plane, a 0.35 micron SiO dielectric layer, and a 0.4 micron top niobium wiring layer. The waveguide probe itself will be laid down as a part of the niobium wiring layer, whereas the ground plane layer will end at the waveguide wall. The SIS junction is connected to the top wiring using a 5 micron square pad to provide for lithography alignment errors. Two additional gold layers are deposited to complete the chip: a bond pad layer for the DC bias and IF output connections and a beam lead layer to connect the niobium ground plane to the waveguide block structure (Fig. 13).
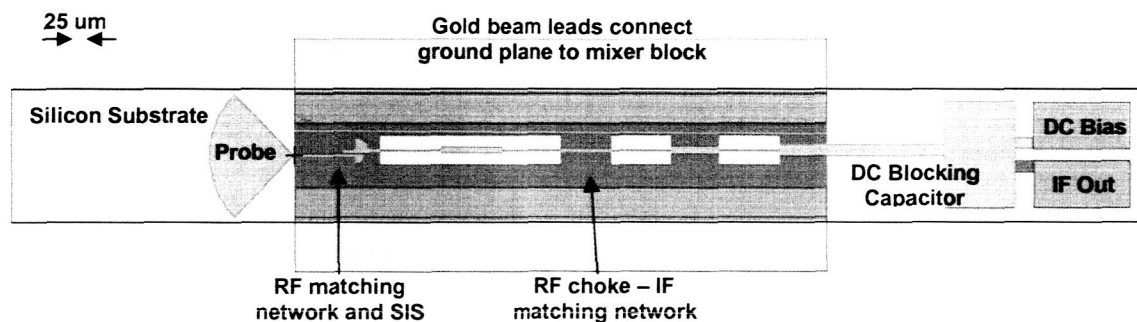

Figure 13: Probe–mixer chip layout. The probe substrate is 25 micron thick silicon, 230 microns wide × 1600 microns long. The circuitry is applied to the top of the substrate using UV contact lithography. The five layers: niobium ground plane; SiO dielectric; niobium wiring; gold bond pads; gold beam leads. The waveguide probe is part of the wiring layer, connecting to the RF matching network. The RF choke uses CPW sections to increase line characteristic impedance; these sections can be identified by the rectangular gaps in the ground plane layer. Minimum wiring line thickness is 2.7 microns.

The ground plane layer must have the same electric potential as the waveguide wall surface at the mouth of the substrate channel or the probe performance will be seriously degraded. This is accomplished by extending the ground plane conductor laterally beyond the edges of the substrate material using beam lead technology similar to that developed at JPL in support of their high frequency multiplier development. The beam leads are electrically mated to the waveguide block structure to ensure that a good ground connection is achieved.

The mixer chip is mounted in a split-waveguide block. The block (Fig. 14) is attached to the corrugated feed horn and also contains a small circuit board for SIS DC bias components. The IF output from the block is via a high-frequency K-type connector which mates directly to the input connector on the low noise IF preamplifier housing. The mixer chip sits in a channel machined in one half of the waveguide block. Its beam leads rest on the block surface on either side of the channel, and are pinched between the two block halves when mated together. The block requires only straightforward mechanical milling; fillet radii in the waveguide are all a generous 5 mils and the waveguide structure is designed so that the receiver performance is tolerant of expected machining accuracies.
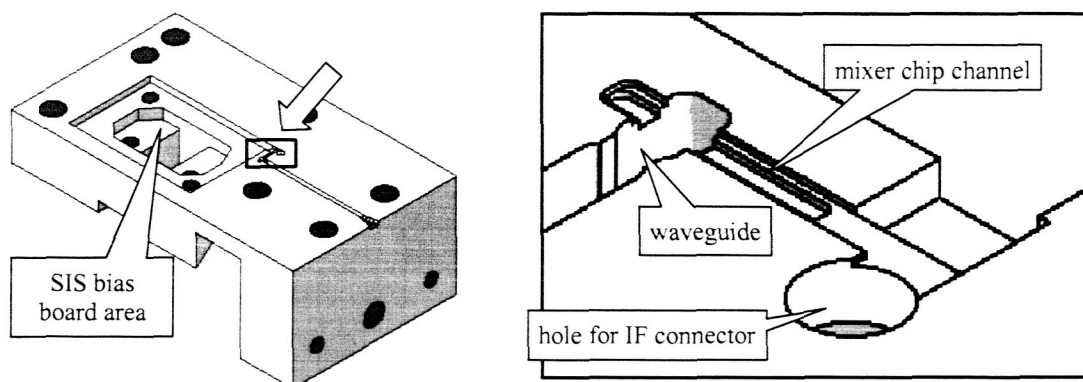
Figure 14: The waveguide block showing the mounting area for the mixer chip. The close-up view on the right uses a viewing angle different from that of the entire block half shown on the left; the arrow indicates the viewing perspective for the close up view. The IF output is via a glass bead to a K-type connector mounted to the bottom surface of the mixer block; the center conductor pin of the glass bead sticks up through the cylindrical hole adjacent to the chip channel. A wire bond connects the pin to the IF output pad on the mixer chip.

7. SUPERMIX

An important part of mixer design effort has included extensive enhancement of the SuperMix software package developed at Caltech to aid in the design and optimization of superconducting submillimeter wave receivers. Designed to run under UNIX or Linux, SuperMix is an extensive C++ software library containing over 47,000 lines of code[6].

The SuperMix class library and its associated programs allow a researcher to write, compile, and run sophisticated circuit simulations of arbitrary complexity. SuperMix provides a complete set of circuit elements suitable for frequency-domain simulations from DC to the terahertz range. The library includes models of SIS quasiparticle tunnel junctions and physical transmission line components such as microstrip and CPW lines. The physical transmission line objects can be built up from layers of normal metal and superconducting films and real dielectrics. SuperMix can perform full harmonic balance calculations of SIS quasiparticle receiver designs of arbitrary complexity as well as mixer gain and noise analyses using any number of harmonics and including any number of SIS junctions[7].

The SuperMix package includes a sophisticated multi-parameter optimizer. Users can tailor the optimizer's error function to their exact needs, and the optimizer can then control any set of device parameters in order to refine a circuit design. To achieve this level of flexibility, SuperMix contains a rather complete numerical math library for manipulation of complex-valued matrix, vector, and scalar functions and objects. It includes robust linear algebra, interpolation, integration, root finding, and minimization routines. More details regarding SuperMix may be found at the SuperMix website: http://www.submm.caltech.edu/supermix/.

8. WIDEBAND CRYOGENIC MMIC LOW-NOISE IF PREAMPLIFIER

The wideband mixer IF output must be amplified using a low noise preamplifier (LNA) with bandwidth and noise performance which will not compromise the overall performance of a receiver. The amplifier must be stable and have predictable and moderate input impedance over a bandwidth of 50 GHz (to avoid out-of-band oscillation or output saturation of the SIS). It should have high gain and a flat frequency response over the 6-18 GHz IF bandwidth as well as noise temperatures below 10 Kelvin across the IF band.

Microwave monolithic integrated circuit (MMIC) technology employing indium phosphide (InP) high electron mobility transistor (HEMT) active elements has been identified as the most promising route to achieving the broadband, low noise performance goals of the LNA. The current device being developed is based on the JPL/Caltech WBA8T series MMIC design, fabricated at TRW. This chip has a 75 micron thick substrate measuring 750 by 2000 microns and has 4

InP HEMT stages. In order to operate at 20 GHz a 150 micron gate width HEMT is used, resulting in good gain over an excellent bandwidth of 2-20 GHz for the four transistor cascade. After characterizing the performance and limitations of current designs, the project has entered a period of design refinement through successive phases of modeling, building, testing, analyzing, and fixing in association with teams at JPL and TRW.

The current design, WBA8T-E, has a flat gain response over the 6–18 GHz IF band, with gain exceeding 20 dB. The input return loss is about 10 dB across this same band (50 ohm source). The amplifier noise temperature at 4K is less than 13K (50 ohm source) over the IF band, and less than 10K from 8 to 15 GHz (Fig. 15).
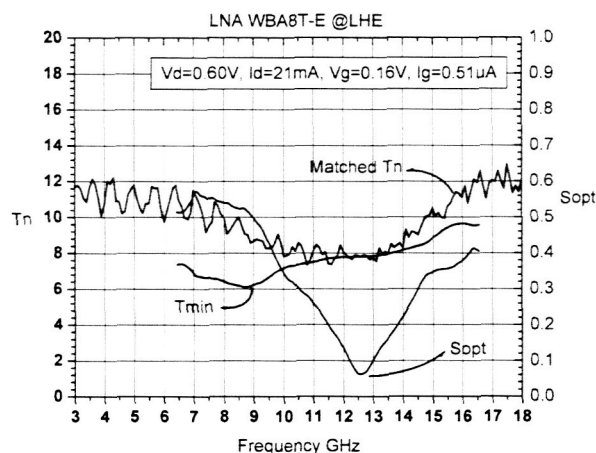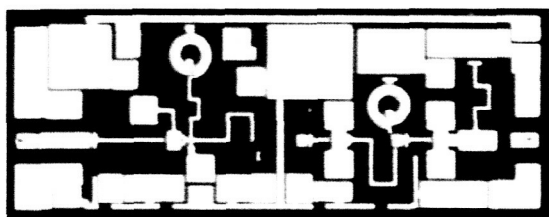

Figure 15: LNA chip and its cryogenic noise performance (measured). The WBA8T-E MMIC, manufactured by TRW, contains 4 InP HEMT stages. Using inductive feedback in the first stage to improve input match while minimizing noise, its gain exceeds 20 dB across the 6–18 GHz IF band, with a minimum noise temperature (T_{min}) of less than 10K when the amplifier is cooled to 4K. The plot shows the measured noise temperature with a 50 ohm source ("Matched Tn") as well.

9. ROOM TEMPERATURE IF WIDEBAND SPECTROMETER SYSTEM

To be effective, the instrument must have an appropriate spectrometer backend to process the receiver's very wide bandwidth IF signal. Fortunately, for the redshift determination application, the expected CO emission lines should be quite broad (approximately 250 MHz), so high spectrometer resolution is not required. A viable solution to this problem is to use an array of medium-resolution spectrometers to cover the entire IF bandwidth. The 128 channel, 0.5–4.5 GHz WASP II analog autocorrelation spectrometer developed by one of the authors (A. Harris) provides a nearly ideal combination of bandwidth and spectral resolution for the CO line search application[2].

The IF system requires an array of IF downconverters which will divide up the IF band into segments and convert the frequency ranges of the segments to a range which matches the bandwidth of the WASP II autocorrelators. A system is being developed which uses three IF downconverter modules; the downconverters are heterodyne mixers which convert their lower sideband inputs to a 0.5–4.5 GHz output range. Each module is a wideband unit so that each channel band will be completely determined by its low-pass filter and local oscillator frequency. A single channel downconverter prototype unit has been built and tested.

Before the LNA output signal is fed to the downconverter system, it must be further amplified by a series of room-temperature, wideband IF amplifiers. A 2–20 GHz amplifier module consisting of three commercial MMIC amplifiers has been developed and tested; it provides a quite flat, 30 dB gain across its bandwidth, with a measured T_n of less than 450K at room temperature and less than 150K if the module is cooled to 77K.

ACKNOWLEDGEMENTS

REFERENCES

1. A. Blain, I. Smail, R. Ivison, J.-P. Kneib, and D. Frayer, "Submillimeter Galaxies," *Physics Reports* (in press, publication expected in 2002). Preprint available at *http://arxiv.org* as astro-ph/0202228.

2. A. Harris and J. Zmuidzinas, "A wideband lag correlator for heterodyne spectroscopy of broad astronomical and atmospheric spectral lines," *Review of Scientific Instruments*, 72#2, 1531. 2001.

3. J. Kawamura, J. Chen, D. Miller, J. Kooi, J. Zmuidzinas, B. Bumble, H. LeDuc, and J. Stern, "Low-noise submillimeter-wave NbTiN superconducting tunnel junction mixers," *Applied Physics Letters*, 75, 4013. 1999.

4. S. Withington, G. Yassin, J. Leech, and K. Isaak, "An accurate expression for the input impedance of one-sided microstrip probes in waveguide," *Proc. Tenth International Symposium on Space Terahertz Tech.* 1999.

5. Y-C Leong and S. Weinreb, "Full-band waveguide-to-microstrip probe transitions," *Microwave Theory and Techniques, Digest of Papers*, IEEE. 1999.

6. J. Ward, F. Rice, and J. Zmuidzinas, "SuperMix: a flexible software library for high-frequency circuit simulation, including SIS mixers and superconducting components," *Proc. Tenth International Symposium on Space Terahertz Tech.* 1999.

7. F. Rice, J. Ward, J. Zmuidzinas, and G. Chattopadhyay, "Fast harmonic balance of SIS mixers with multiple junctions and superconducting circuits," *Proc. Tenth International Symposium on Space Terahertz Tech.* 1999.

C 2002 NASA Monterey Detector Conference Paper

A WIDE-BANDWIDTH, LOW-NOISE SIS RECEIVER DESIGN FOR MILLIMETER AND SUBMILLIMETER WAVELENGTHS

Matthew Sumner[1], Andrew Blain[1], Andrew Harris[2], Robert Hu[3], Henry G. LeDuc[4], David Miller[1], Frank Rice[1], Sander Weinreb[4], Jonas Zmuidzinas[1]

[1]California Institute of Technology, Pasadena, CA 91125
[2]Department of Astronomy, University of Maryland, College Park, Maryland 20742
[3]University of Michigan, c/o Caltech, MS 320-47, Pasadena, CA 91125
[4]Jet Propulsion Laboratory, Pasadena, CA 91109

ABSTRACT

In principle, millimeter and submillimeter heterodyne receivers using state-of-the-art SIS detectors are capable of extremely large instantaneous bandwidths with noise temperatures within a few Kelvin of the quantum limit. We are applying modern design tools, such as 3D electromagnetic simulators and Caltech's *SuperMix* SIS analysis package, to develop a new generation of waveguide SIS mixers with very broad RF and IF bandwidths. Our initial design consists of a double-sideband mixer targeted for the 180 – 300 GHz band that uses a single SIS junction excited by a full bandwidth, fixed-tuned waveguide probe on a silicon substrate. The IF output band, limited by the MMIC low-noise IF preamplifier, is 6 – 18 GHz, providing an instantaneous RF bandwidth of 24 GHz (double-sideband). The SIS mixer conversion loss is predicted to be no more than 1 – 2 dB (single-sideband) with mixer noise temperatures across the band within 10 Kelvin of the quantum limit. The single-sideband receiver noise temperature goal is 70 Kelvin. The wide instantaneous bandwidth and low noise will result in an instrument capable of a variety of important astrophysical observations beyond the capabilities of current instruments. Lab testing of the receiver will begin in the summer of 2002, and a demonstration on the CSO should occur in the spring of 2003.

INTRODUCTION

Heterodyne receivers currently in use on major telescopes typically offer an IF bandwidth of a few GHz, although some recent designs have achieved 8 GHz.[1] Extending this bandwidth even further would be highly desirable, as several applications would benefit greatly from this improvement.

Surveys using submillimeter cameras (such as SCUBA and MAMBO) have resulted in the discovery of roughly 200 very luminous galaxies. These sources appear to be at high redshifts, although only a handful have been precisely measured.[2] The redshifts can be determined using the spectral lines of several molecules (particularly CO) that can be observed in the millimeter band. However, the high redshifts of these objects make it difficult to predict the observed line frequencies, and the lines can only be found by searching a large fraction of the 190 – 320 GHz atmospheric window. Since these are such faint sources, each observation requires several, or even tens, of hours per LO frequency, even with a sensitive receiver. A wide-bandwidth receiver decreases the required number of LO settings, greatly reducing the total observing time and making it practical to build up a statistical sample of redshifts. Spectral line surveys of star-forming regions would also benefit from expanded receiver bandwidths.

In the Earth Sciences community, broadband receivers would be very useful for studying the Earth's atmosphere. The atmospheric abundances of several important molecules can be mapped by detecting their spectral-line emissions at millimeter wavelengths (near 230 GHz). Two generations of satellites have been built that use this technique to provide considerable information on atmospheric chemistry, ozone depletion, and the global effects of pollution.[3] As the next step in this research, a new satellite mission, the Scanning Microwave Limb Sounder (SMLS), has been proposed that would provide a much larger data rate, allowing for higher resolution and better coverage. A receiver with a large bandwidth and low noise would be required to allow the satellite to measure multiple spectral lines accurately and rapidly with each pointing of the antenna.

Contact information for M. Sumner: Email: sumner@caltech.edu, phone (001) 626 395 4246

RECEIVER DESIGN

In order to address some of these needs, we have developed a new receiver design with an eye toward maximizing the bandwidth while maintaining a low noise temperature. Our initial design consists of a double-sideband receiver using a single SIS junction. Intensive simulations, combined with preliminary measurements, indicate that the design will offer a 12 GHz IF bandwidth (6 – 18 GHz), corresponding to a double-sideband RF bandwidth of 24 GHz, while maintaining a noise temperature that is competitive with narrower bandwidth designs.

Mixer Circuit Design

The heart of the RF mixer is an Nb-AlN-Nb SIS junction. We expect the 1.3×1.3 micron junction to have a critical current density (J_c) of 14 kA/cm^2, resulting in a normal resistance (R_n) of 8.5 Ω, and a junction capacitance of 144 fF. The junction size is suitable for UV contact lithography, and the R_nC product corresponds to a frequency of 130 GHz. Current technology at JPL can produce such junctions with very high quality, and subgap-to-normal resistance ratios in excess of 20 should be attainable.

The SIS junction is coupled to the waveguide probe using a thin-film, superconducting microstrip matching network consisting of a ¼-wave transformer followed by a two-section LC ladder (see Figure 1-a). The RF network tunes out the junction capacitance and matches the 36 Ω probe to the 9 Ω junction impedance. The IF output is extracted from the low impedance, fan end of the large radial-stub capacitor.

The IF output then passes through a CPW/microstrip filter ladder that provides RF isolation and matches the junction to the 50 Ω IF amplifier. The IF signal is coupled to the amplifier via a DC blocking capacitor just before IF wirebond pad at the right side of Figure 1-a. DC bias for the SIS junction is provided through a separate wirebond pad to the left of the DC blocking capacitor.

The niobium ground plane is 0.2 microns thick, and the niobium wiring thickness is 0.4 microns. The conductors are separated by a 0.35 micron thick SiO layer. The layout is suitable for UV contact lithography and uses a minimum wire width of 3.0 microns in the RF section. The ground plane extends just to the waveguide wall and is shorted to the waveguide block along each edge of the substrate using thick gold pads which contact the upper half of the split waveguide block when the block is assembled.

The entire circuit has been modeled and optimized by C++ programs using the *SuperMix* library. Figure 1-b shows the modeled performance of the optimized mixer chip design. Clearly, powerful software tools like *SuperMix* and *Ansoft HFSS* can improve the performance and lower the technical risk of current design efforts.
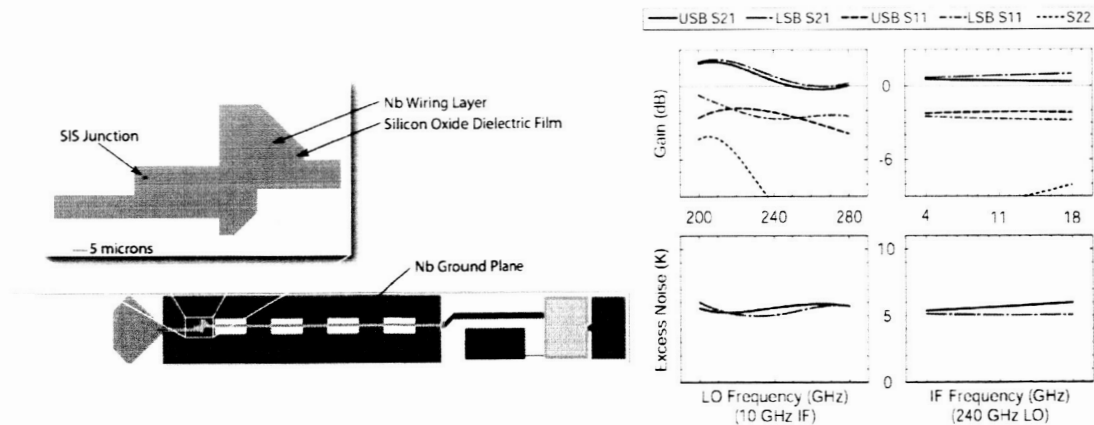

Figure 1-a (left): Preliminary mask layout for the SIS mixer chip. The broadband radial-stub probe (at left) couples the signal from the waveguide into the RF matching network (shown in the enlargement). The IF output is picked off from the low-impedance, outer edge of the radial-stub capacitor (at the right side of the inset). The IF signal then travels through a CPW/microstrip filter ladder (for RF isolation) to the bonding pad at the far right end of the chip. DC bias is provided through the bonding pad just to the left of the large DC blocking capacitor.

Figure 1-b (right): Simulated performance of mixer circuit showing the gain and the noise in excess of the quantum limit (which is approximately 10 – 15 K at these frequencies). The circuit is expected to achieve a noise temperature less than twice the quantum limit.
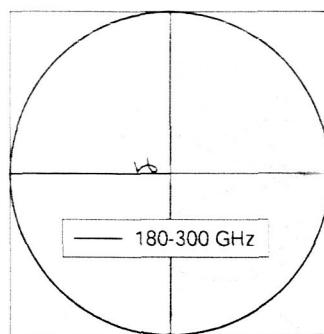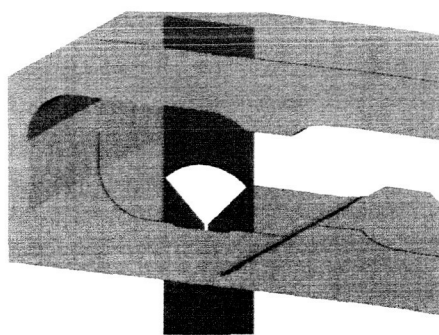
Figure 2-a (left): *Broadband probe and mixer chip shown in relation to waveguide (also see Figure 1-a). The faint line indicates the split plane in the mixer block. The small tuning step upstream of the probe and the fixed backshort were optimized using HFSS and SuperMix.*

Figure 2-b (right): *Predicted performance of probe based on HFSS model, plotted on a 50 Ω Smith chart. The probe offers an almost real impedance of $(36 + j\,2)$ Ω over the $180 - 300$ GHz range of the receiver.*

Broadband Probe

The RF signal is coupled to the SIS device through a radial-stub waveguide probe that covers the receiver's $180 - 300$ GHz operating range. As shown in Figure 2-b, the probe impedance remains essentially constant and very nearly real over the 1.7:1 frequency range, with an approximate value of 36 Ω.

The waveguide includes a fixed backshort and a small capacitive tuning step just upstream of the probe (Figure 2-a). The configuration was designed by modeling the individual components in *Ansoft HFSS* and importing their behaviors into a C++ circuit model based on the *SuperMix* library, which was used to optimize the backshort and tuning step. The results shown were generated from an *HFSS* model of the entire probe and waveguide structure. These results have been validated for a very similar design by comparing the *HFSS* results to scale-model measurements.

Cryogenic Low-Noise Preamplifier

The IF output of the mixer must be amplified using a low-noise preamplifier with bandwidth and noise characteristics that will not compromise the overall performance of the receiver. Microwave monolithic integrated circuit (MMIC) technology employing indium phosphide (InP) high electron mobility transfer (HEMT) active elements has been identified as the most promising route to achieving these goals. We are currently refining a design, based on the JPL/TRW WBA8T MMIC, that uses a 75 micron thick substrate with three 200 micron InP HEMT stages (Figure 3-a). The latest iteration of this design uses inductive feedback to minimize noise, and preliminary measurements of its performance at 4 K indicate that it offers at least 20 dB of gain with a noise temperature below 10 K from 6 to 10 GHz (Figure 3-b). These measurements are consistent with simulations that predict similar performance across the entire 6 – 18 GHz IF band of the receiver.
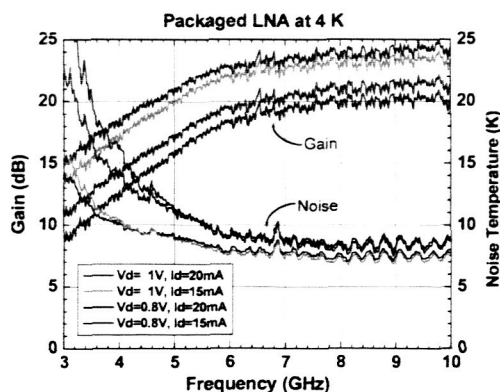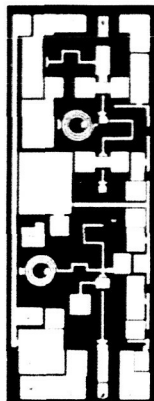

Figure 3-a (left): *Picture of the IF preamplifier circuit. This version, based on the JPL/TRW WBA8T MMIC, uses three InP HEMT stages and inductive feedback to minimize noise.*

Figure 3-b (right): *Preliminary measurements of the preamplifier's performance at 4 K. These results are consistent with simulations predicting that the preamplifier can achieve over 20 dB of gain with a noise temperature below 10 K across the entire 6 – 18 GHz IF band of the receiver. (The limited frequency range and the "ripple" that can be seen in the data are limitations of the test setup and will be corrected in future measurements.)*

IF System and Wideband Spectrometer

For astrophysical observations at the CSO, the receiver will be used with the WASP2 spectrometer to search for spectral lines from submillimeter sources. Developed at the University of Maryland, WASP2 is a wideband lag correlation spectrometer offering a 3.6 GHz bandwidth.[4] To match this bandwidth, the room-temperature IF system will consist of several down-converters that will divide the IF signal into four bands. Each band will be analyzed by a WASP2 unit, allowing us to utilize the entire 12 GHz bandwidth of the receiver.

The IF system will also include a wideband amplifier that has been developed for this purpose. The device, consisting of three commercial MMIC amplifiers, offers 30 dB gain over a 2 – 20 GHz bandwidth. The amplifier has been designed, built, and tested (Figure 4).

SUPERMIX

The design of this receiver has relied heavily on the use of *SuperMix*, a software package developed at Caltech that provides a complete set of circuit elements suitable for frequency-domain simulations from DC to THz frequencies. The library allows for accurate modeling of superconducting transmission line elements and predicts the nonlinear SIS mixing performance using Tucker's quantum mixing theory. In addition, the *SuperMix* package includes a sophisticated multi-parameter optimizer that can be used to refine a circuit design by modifying any device characteristics. For more information, visit *http://www.submm.caltech.edu/supermix*.
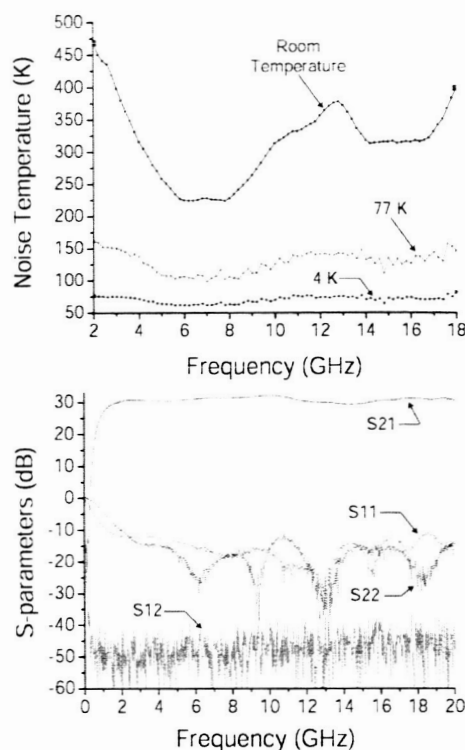

Figure 4: Measured performance of room-temperature IF amplifier. The design offers low-noise (top) and a 30 dB gain (bottom) across the IF bandwidth of the receiver.

SUMMARY

We present the design for a low-noise receiver that has been optimized to provide a wide IF bandwidth (6 – 18 GHz) in the 180 – 300 GHz range. The initial design consists of a double-sideband receiver that will offer an instantaneous RF bandwidth of 24 GHz, with a single-sideband receiver noise temperature goal of 70 Kelvin. Already, some elements have been built, and lab testing of the full receiver should begin in a few months. While our initial demonstration of this new design will focus on redshift surveys in the 180 – 300 GHz range, we plan to push this design to higher frequencies in the future. Such wide-bandwidth mixers will be very useful for our CASIMIR instrument for SOFIA.

ACKNOWLEDGEMENTS

REFERENCES

1. Lauria, E. F., A. R. Kerr, M. W. Pospieszalski, S.-K. Pan, J. E. Effland, A. W. Lichtenberger. "A 200 – 300 GHz SIS Mixer-Preamplifier with 8 GHz IF Bandwidth." *ALMA Memo 378*. June 7, 2001. (Available at *http://www.alma.nrao.edu/memos/index.html*.)

2. Blain, Andrew W., Ian Smail, R. J. Ivison, J.-P. Kneib, and David T. Frayer. "Submillimeter Galaxies." *Physics Reports*, vol. 369, p. 111 – 176 (October 2002).

3. Waters, Joe. "The EOS Microwave Limb Sounder (MLS) Experiment." Oct. 10, 2000. (Available at *http://mls.jpl.nasa.gov/joe/eos_mls_summary_presentation.pdf*.)

4. Harris, A. I. and J. Zmuidzinas. "A Wideband Lag Correlator for Heterodyne Spectroscopy of Broad Astronomical and Atmospheric Spectral Lines." *Review of Scientific Instruments*, vol. 72, no. 2, p. 1531 – 1538 (February 2001).

D   2002 NASA Monterey Detector Conference Poster

An Extremely Wide Bandwidth, Low Noise SIS Heterodyne Receiver Design For Millimeter And Submillimeter Observations

Matthew Sumner[1], Andrew Blain[1], Andrew Harris[2], Robert Hu[3], Frank Rice[1], Sander Weinreb[4], Jonas Zmuidzinas[1]

[1]California Institute of Technology, [2]University of Maryland, [3]University of Michigan, [4]Jet Propulsion Laboratory

Introduction

Our group has designed a heterodyne submillimeter receiver that offers a very wide IF bandwidth of 12 GHz, while still maintaining a low noise temperature. The 180-300 GHz double-sideband design uses a single SIS device excited by a full bandwidth, fixed-tuned waveguide probe on a silicon substrate. The IF output frequency (limited by the MMIC low noise IF preamplifier) is 6-18 GHz, providing an instantaneous RF bandwidth of 24 GHz (double-sideband). Intensive simulations predict that the junction will achieve a conversion loss better than 1-2 dB and a mixer noise temperature of less than 20 K across the band (twice the quantum limit). The single sideband receiver noise temperature goal is 70 K.

The wide instantaneous bandwidth and low noise will result in an instrument capable of a variety of important astrophysical and environmental observations beyond the capabilities of current instruments (see insets below). Lab testing of the receiver will begin this summer, and first light on the CSO should be in the spring of 2003. At the CSO, we plan to use receiver with WASP2, a wideband spectrometer, to search for spectral lines from SCUBA sources. This approach should allow us to rapidly develop a catalog of redshifts for these objects.

Astrophysics Applications

Recent surveys using submillimeter cameras (such as SCUBA and MAMBO) have resulted in the discovery of roughly 200 very luminous galaxies. These sources appear to be at high redshifts, although only a handful have been precisely measured. In principle, the redshifts can be determined using spectral lines from several molecules (particularly CO) that can be observed in the submillimeter band; however, because of the high redshifts of these objects, a large fraction of the 190-320 GHz atmospheric window must be searched to find these lines. Since these are faint sources requiring long integration times, a low-noise, high-bandwidth receiver is vital for making these measurements.
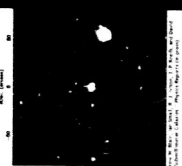
Figure: A deep optical image overlaid with contours indicating the submillimeter sources found by SCUBA. Spectral redshifts would aid in associating these objects with sources at other wavelengths.

Earth Sciences Applications

The atmospheric abundances of several important molecules can be mapped by detecting their spectral-line emissions at submillimeter wavelengths (near 230 GHz). Two generations of satellites have been built that use this technique to provide considerable information on atmospheric chemistry, ozone depletion, and the global effects of pollution. As the next step in this research, a new satellite mission, the Scanning Microwave Limb Sounder (SMLS), has been proposed that would provide many more data points, allowing for higher resolution and better coverage. To accomplish these goals, the SMLS requires a very wide bandwidth, low noise heterodyne receiver.
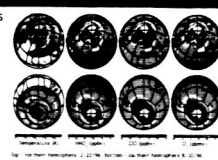
Figure: Data taken by the EOS Microwave Limb Sounder (MLS) experiment showing temperature, HNO_3, ClO, and O_3 in the lower stratosphere.

Receiver Design

Mixer Circuit

The heart of the RF mixer is an Nb-AlN-Nb SIS junction. The 1.3×1.3 micron junction will have a critical current density (J_c) of 14 kA/cm^2, resulting in a normal resistance (R_n) of 8.5 Ω and a junction capacitance of 144 fF. The junction size is suitable for UV contact lithography, and the $R_n \times C$ product corresponds to a frequency of 130 GHz. Current technology at JPL can produce such junctions with very high quality, so a subgap-to-normal resistance ratio in excess of 20 should be easily attainable.

The SIS junction is coupled to the waveguide probe using a thin-film, superconducting microstrip matching network (shown in the enlargement below, against a grid of 5x5 microns). The network consists of a ¼-wave transformer followed by a two-section LC ladder. The RF network tunes out the SIS junction capacitance and matches the 36 ohm probe to the 9 ohm junction impedance. The IF output is extracted from the low impedance, fan end of the large radial-stub located at the upper-left in the figure.

Simulated performance of mixer circuit showing gain and noise in excess of the quantum limit.
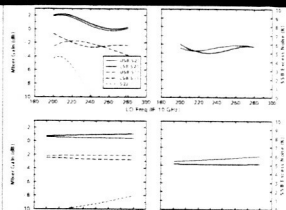
The IF output is coupled to the preamplifier using a CPW/microstrip filter ladder that provides RF isolation and matches the junction to the 50 Ω IF load (as shown in the large figure to the left). The IF signal is then coupled via a DC blocking capacitor to the IF wirebond pad at the top of the figure at left. DC bias for the SIS junction is provided through the blue wirebond pad just below the DC blocking capacitor.

The niobium ground plane is 0.2 microns thick, and the wiring thickness is 0.4 microns. The conductors are separated by a 0.35 micron thick SiO layer. The layout is suitable for UV contact lithography and uses a minimum wire width of 3.0 microns in the RF section.

The ground plane extends just to the waveguide wall and is shorted to the waveguide block along each edge of the substrate using thick gold pads which contact the upper half of the split waveguide block when the block is assembled.

The entire circuit has been modeled and optimized by C++ programs using the SuperMix library. The figure in the upper-right shows the modeled performance of the optimized mixer chip design. Clearly, powerful software tools like SuperMix and Ansoft HFSS can improve the performance and lower the technical risk of current design efforts.

Preliminary mask layout of the thin-film mixer circuitry, built on a silicon substrate. The red and blue layers are the niobium ground plane and wiring, respectively, and the green layer is the silicon oxide dielectric film. The left figure shows the entire mixer chip, while the enlargement at right details the RF matching network.

Broadband Probe

The RF signal is coupled to the SIS device through a radial-stub waveguide probe that covers the operating frequency range of the receiver (180 - 300 GHz). As shown in the figure, the probe impedance remains essentially constant over the 1.7:1 frequency range, with a nominal impedance that is very nearly real.

The waveguide includes a fixed backshort and a small capacitive tuning step just upstream of the probe. The configuration was designed by first modeling the individual components in Ansoft HFSS and importing their behaviors into a C++ circuit model written using the SuperMix library, which was used to optimize the backshort and tuning step.

The results shown were generated using HFSS modeling of the entire probe and waveguide structure. These results have been validated for a very similar design by comparing the HFSS results to scale model measurements.

Simulated probe performance.

Detail showing probe, backshort, and waveguide tuning elements.

Cryogenic Low-Noise Preamplifier

The IF output of the mixer must be amplified using a low noise preamplifier with bandwidth and noise characteristics that will not compromise the overall performance of the receiver. Microwave monolithic integrated circuit (MMIC) technology employing indium phosphide (InP) high electron mobility transfer (HEMT) active elements has been identified as the most promising route to achieving these goals. We are currently refining a design based on the TRW WBA8T MMIC, which uses a 75 micron thick substrate with four 150-micron InP HEMT stages. The latest iteration of this design uses inductive feedback to minimize noise, and preliminary measurements indicate that it offers 20+ dB of gain with a noise temperature below 10 K.
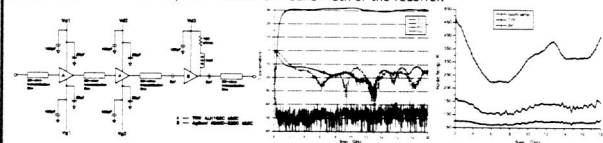
The figures below show the simulated (left) and measured (right) performance of the preamplifier. The purple curve in the simulated measurements shows that the noise temperature is predicted to be less than 10 K across the entire band at 4 K. The actual measurements (taken at 4 K) were limited to frequencies below 10 GHz; however, over that range, they demonstrate noise temperatures of 7-9 K. (The limited frequency range, as well as the "ripple" that can be seen in that data, are limitations of the test setup and will be corrected in future measurements.)

Preamplifier circuit with close-up of first stage.
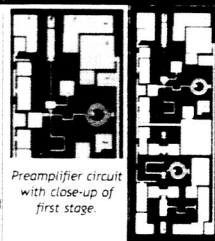
Left: Simulated performance of preamplifier. Right: Measured performance at 4 K.

Final IF Amplifier

The final stage of the receiver is an amplifier that can be used at room temperature or at 77 K. The design uses three commercial MMIC amplifiers, as shown in the figure below. The amplifier has been designed, built, and tested, and results are shown for the 2- 20 GHz band. It can achieve a 30 dB gain, with less than 3 dB variation, over the entire IF bandwidth of the receiver.
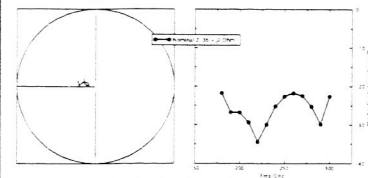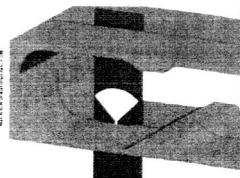
Left: Circuit design for IF amplifier. Middle and Right: Measurements of scattering parameters and noise for the IF amplifier.

WASP2 Spectrometer

For astrophysical observations at the CSO, we plan to use the WASP2 spectrometer with the receiver to search for spectral lines in the submillimeter sources that have been observed by the SCUBA instrument. WASP2 is a wideband lag correlation spectrometer being developed at the University of Maryland that can cover a 3.6 GHz bandwidth. By combining several of these instruments, we will be able to utilize the entire 12 GHz bandwidth of the receiver.
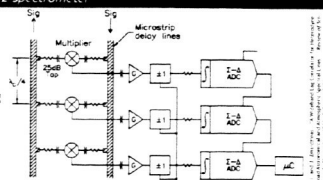
Schematic of WASP2 spectrometer

SuperMix

The design of this receiver has benefitted greatly from the use of SuperMix, a software package developed at Caltech that provides a complete set of circuit elements suitable for frequency-domain simulations from DC to THz. The library allows for accurate modeling of superconducting transmission line elements and predicts the nonlinear SIS mixing performance using Tucker's quantum mixing theory. In addition, the SuperMix package includes a sophisticated multi-parameter optimizer that can be used to refine a circuit design by modifying any device characteristics. For more information, visit http://www.submm.caltech.edu/supermix.